Computational Modeling of High Data-rate Laser Communication in Turbulent Atmosphere

Gennady P. Berman, T-4/T-CNLS; Alan R. Bishop, ADTSC; Boris M. Chernobrod, T-4; O.O. Chumak, T-4, National Academy of Sciences of Ukraine, Institute of Physics; Vyacheslav N. Gorshkov, T-4/T-CNLS, National Technical University of Ukraine, and National Academy of Sciences of Ukraine, Institute of Physics; S.V. Torous, National Technical University of Ukraine

The scintillations of intensity (SI) of a laser beam caused by the influence of atmospheric turbulence are a major obstacle for gigabit data rates and long-distance optical communications [1,2]. In the process of propagation of the laser beam through turbulent atmosphere with a given strength, C_n^2, the signal (intensity, I^l) at the detector depends on the state (realization) of atmosphere, l. One of the main factors contributing to the

$$\mathrm{SI},\ \sigma^2 = \langle (I^l)^2 \rangle_l / \langle I^l \rangle_l^2 - 1$$

is a beam fragmentation, which results in a decay of the initial laser beam into a set of separated beams. Some of these beams may not be detected if the size of detector is smaller than the characteristic distance between the beams. Moreover, depending on l, the coherent beam initially oriented along the z-axis deviates as a whole in the x-y plane. This deviation is characterized by the beam wandering [3], (Fig. 1).

$$\vec{r}_w^{\,l}(z) = \int \vec{r} I^l(x,y,z)\,dxdy \Big/ \int I^l(x,y,z)\,dxdy \cdot$$

The integral dependence of the intensity, I^l, on r_w^i contributes to the high level of scintillations, σ^2, at the detector.

It is known that a partially coherent beam (PCB) in combination with a slow-time-response detector leads to a significant reduction of the SI. However, this time-averaging (slow detector) technique is incompatible with gigabit data rate. Recently, we proposed a new method for the reduction of scintillations that combines a time averaging of a PCB with a spectral encoding [4-7]. In our approach, the information is encoded in the form of dips in the spectrum of subpicosecond coherent laser pulses.

The key component of the proposed technique is a phase diffuser (or phase modulator, PM), which prepares the PCB. The results obtained in our numerical experiments demonstrate that an appropriately chosen PM can significantly suppress the SI. In particular, one can try to suppress the effect of wandering by using a PM that deflects the laser beam as a whole in different directions, e_m, for fixed l. (This beam is a particular case of a PCB, as its phase changes in the plane $z = 0$. At the same time, its wave front remains flat for each realization of the PM in the plane transverse to the direction of propagation.) In this case, some of the directions, $\vec{e}_m$, will contribute to the compensation of wandering (see the insert in Fig. 2), and an average over the PM realizations signal at the detector,

$$\hat{I} = \frac{1}{M} \sum_{m=1}^{M} I_m^l ,$$

can become rather stable-independent (or weakly dependent) of the atmospheric realization, l.

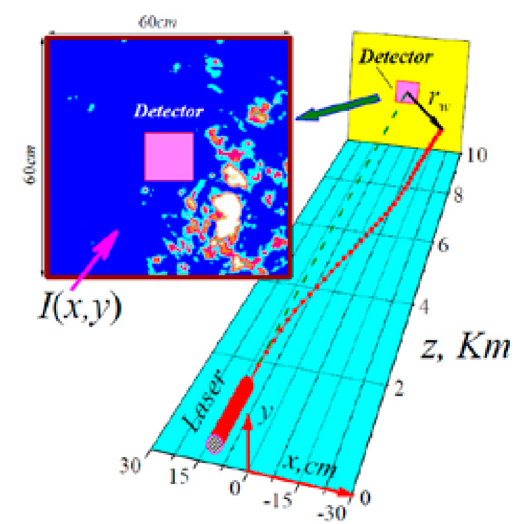

Fig. 1. Propagation of initially coherent laser beam through turbulent atmosphere (λ = 1.55 µm; radius of laser beam, r_0 = 2cm; $C_n^2 = 2.5\mathrm{x}10^{-14} m^{-2/3}$). An example of numerical simulations that demonstrates both fragmentation and wandering for a single atmospheric realization, l.

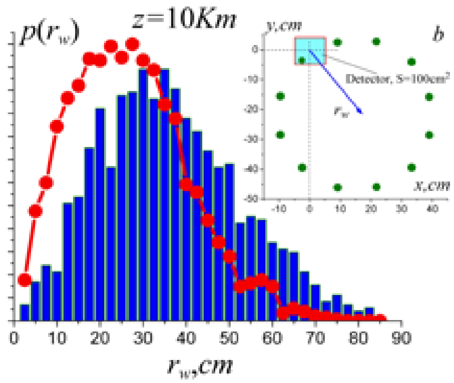

Fig. 2. The red curve is the distribution function, $p(r_w)$, for a coherent beam propagating initially along the z-axis, at $z = D = 10km$. The insert shows the coordinates of the centers of PCB for random realization of atmosphere, l, $\vec{r}^{\,l}_{m,c}(z) = \int \vec{r} I^l_m(x,y,z)dxdy / \int I^l_m(x,y,z)dxdy$, with angles, $\theta \approx tg\theta = r_{w,max}/D$, to the axis $z(p(r_{w,max} = 25cm) = p_{max})$. The blue color diagram, $p(r_c)$, corresponds to a distribution function for a PCB.

In [8] we present the results of the numerical experiment for a fixed set of vectors, $\vec{e}^{\,(i)}_m$, $m = 1,2...,12$; $i = 1,2,3$. These vectors are deflected from the z-direction by the same angles, $\boldsymbol{\theta}_i = \rho_i/D$ ($\rho_{1,2,3}$ = 15cm, 25cm, 35cm), and their projections on the x-y-plane are *homogeneously* distributed azimuthally (the angle, φ, between the neighboring projections was chosen to be 30°). The angles $\boldsymbol{\theta}_i$ were chosen by the following protocol. In Fig. 2, the distribution function, $p(r_w)$, is presented in a red color in the x-y-plane and at $z = D = 10km$ for the coherent beam oriented initially along the z-axis. As one can see, the most probable deviation (wandering) is, $15cm \leq r_w \leq 35cm$. Then, for a PCB the angles $\boldsymbol{\theta}_i$ were chosen by taking into account this wandering parameter.

Figure 3 demonstrates the main result, which indicates an efficient suppression of the SI derived by averaging over 36 directions of the PCB. Note that in this protocol, the set of realizations for the PM can be chosen to be small, and it can be similar for all atmospheric realizations: A random choice of realizations from a continuous set, $\{\vec{e}\}$, is not required.

In conclusion, our numerical results demonstrate that the intensity scintillations can be significantly reduced by using a partially coherent beam with a particular realization of the phase modulator. This direction appears to be very promising for real implementations.

For more information contact Gennady Berman at gpb@lanl.gov.

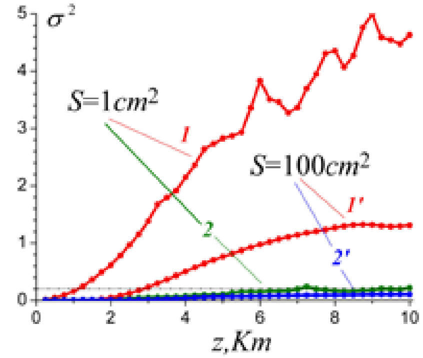

Fig. 3. The dependence of $\sigma^2(z)$ on distance (curves 1,1′ the result for a coherent beam); S is the area of detector. Curves 2 and 2′ are calculated for average signal $\hat{I} = \frac{1}{36}\sum_{m,i} I^l_{m,i}$.

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